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To cite this article: A H Abed and S E Shcheklein 2020 *J. Phys.: Conf. Ser.* **1677** 012003

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Unsteady forced convection heat transfer of a stationary and rotating sphere: Experimental Investigation

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Abstract. Unsteady forced convection heat transfer of a stationary and rotating sphere in an open-loop air system was experimentally investigated with an aim to evaluate the influence of sphere rotation rate on the heat transfer enhancement. A special-purpose conical diffuser having a circular cross-section with constant divergence angle has been carefully designed and adopted as a passive rotating technique. The effect of inlet Re number, non-dimensional rotational speed, and initial surface temperature on heat transfer enhancement are examined. It is observed from the comparison made that there are significant differences between the stationary and rotating sphere of heat transfer behavior. The experimental results of heat transfer behavior in terms of heat flux q and Nusselt number Nu , respectively, expose that q decreases with increase of non-dimensional rotational speed, while Nu increases with the increase of non-dimensional rotational speed around 600%.

1. Introduction

Heat and mass transfer from a stationary/rotating sphere in the fluid field has been an ongoing research topic for many years due to its importance in several industrial applications such as gas-cooled nuclear reactor, chemical, or electrochemical process industries, astrophysics, and aeronautical engineering [1]. Significant research efforts have been made into investigating the heat and mass transfer of a stationary/rotating sphere over a wide range of Reynolds numbers based on experimental and numerical results [2-9]. For rotational systems, the early experimental investigation for the forced convection heat transfer from a rotational single sphere to a fluid flow was done by Kobashi [3], and Tieng et al. [4]. Kreith et al. [5] have broadly investigated the sphere heating and cooling process in air, oil, and water with the turbulent and laminar flow regime. The heat-transfer measurements techniques were conducted by using an electric motor whose rotational speed could be regulated from 30 to 2500 r.p.m. They pointed out that parameters such as rotation rate, surface heat flux, and fluid flow rate greatly influence the heat transfer characteristics of a rotating heated sphere. In the numerical model, the heat transfer characteristics are described by classical boundary-layer theory based on the Navier-Stokes equations. The average heat transfer coefficient and flow engendered by a rotating sphere have been studied numerically by Niazmand et al. [6], Bluemink et al. [7], El-Shaarawi et al. [8], and the temperature profile in the near of a heated sphere have been investigated by Feng [9] in the laminar flow regime. Additional discussions about the hydrodynamic forces model related to the rotating sphere can be viewed in [10-14]. The hydrodynamic interaction between two rotating spheres in tandem arrangement placed in an incompressible couple stress fluid at low Reynolds numbers has



been investigated numerically by Ashmawy [15]. Öztürk [16] numerically studied the unsteady laminar mixed convection of a rotating isothermal sphere in the presence of buoyancy force and magnetic field. They highlighted that the mixed convection as a resultant impact composed of free and forced convection. The results depict that local Nusselt numbers affected by magnetic parameter and buoyancy forces decrease with time due to the impulsive rise of the sphere surface temperature. This paper will analyze and discuss the experimental investigation of the unsteady forced convection of a rotating sphere in an open-loop air system. A special-purpose conical diffuser with a constant divergence angle has been modeled and designed based on the sphere diameter to use it as a passive rotating technique. Average Nusselt number was assessed throughout cooling experiments under a range of Reynolds numbers ($Re = 15000-40000$). In addition, a comparative study on a stationary and rotating heated sphere was performed with an aim to quantify the heat transfer enhancement. The lumped capacity system based on the experimental approach was utilized as a heat-transfer measurement model.

2. Experimental setup and the heat-transfer measurements procedure

2.1. Test apparatus

This investigation focused on the analysis of heat-transfer characteristics of a stationary/rotating sphere during unsteady-state conditions. In heat-transfer measurements, it has already been reported in the literature that there are substantial disparities in the results. These could be connected with the instrumentation and design problems of the test sphere. In view of this, a complete detailed description of the experimental setup will be provided. The schematic diagram describing details of the experimental apparatus used for this experiment is shown in Fig. 1 whereas the test section with a rotating sphere and coordinate system are given in Fig. 2. The experimental setup includes an electric industrial fan, orifice meter, conical diffuser, test sphere, high-frequency induction station as a heating system, and data acquisition units. A forced-air induced by the industrial fan enters the orifice meter section and the settling tank through a circular tube having a 40mm diameter. The volumetric air flow rate was adjusted and measured using a control valve and orifice meter calibrated by a vane-type anemometer. To reduce the flow fluctuations and get a uniform flow at the test section, a settling chamber was used. Conical diffuser having a circular cross-section with a constant divergence angle has been carefully designed as a passive rotating technique based on the sphere diameter. The diffuser of about 800mm length was made from clear Pyrex glass for withstanding high working temperatures. The size of the small end of the diffuser was the same as the inside diameter of the downstream tube, and the size of the large end of the diffuser was 46mm with 2.5mm wall thickness. High-frequency (100 KHz) electromagnetic induction (HFEMI) is a type of heating system that uses high-frequency electricity induction was adopted in this experiment as a heating system. The induction coil was constructed of a copper tube with a 55 mm inner diameter installed directly around the conical diffuser and testing sphere. For a stationary/rotating test, the heat-transfer measurements were conducted with a chrome steel sphere having a diameter of 35mm. During the experiments, the initial sphere temperature ranges from 300 to 100°C. Two temperature measurement methods were used in this experiment: thermocouple measurement and infrared thermography (IR) measurement. To measure the sphere temperature in a stationary test, Fast response thermocouples were positioned in 0.5-mm holes drilled inside the sphere. In addition, temperatures of inlet and outlet were recorded by three thermocouples positioned at the inlet of the test section and two thermocouples positioned at the outlet of the test section, respectively. All thermocouples were connected to a multichannel digital thermometer with MSD200 data logger. For a rotating test, an infrared imaging camera was employed to record the surface temperature profile and ATT-6000 non-contact tachometer to measure the angular velocity.

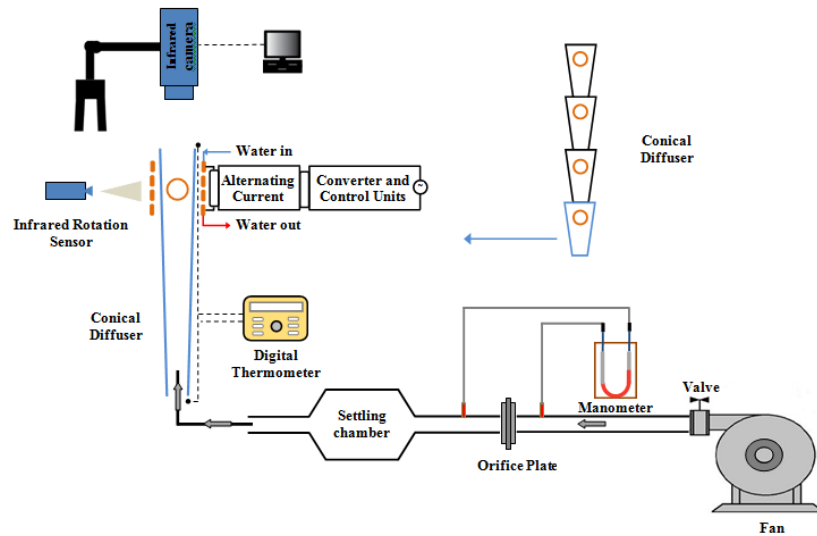


Figure 1. Schematic diagram of the experimental apparatus.

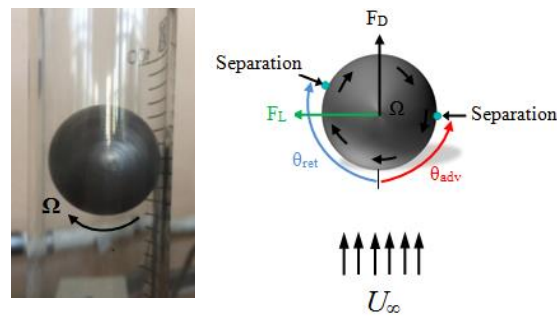


Figure 2. Test section with a rotating sphere and coordinate system.

2.2. Heat-transfer measurements

During the unsteady heat transfer process, when the heated sphere subjected to an airflow stream, unsteady heat conduction inside the sphere occurred, in which the temperature of the sphere decreased with time. For small Biot numbers (Bi), the temperature change inside the sphere is so small and can be neglected. In view of this, the lumped capacity system can be utilized as a heat-transfer model. Basically, for a heated sphere rotating in an airflow stream, the average heat-transfer rate is equal to the sum of convective and radiation heat-transfer coefficients, or,

$$h_{av.} = h_c + h_r \quad (1)$$

Due to the low sphere temperature ($T_s \leq 300^\circ\text{C}$), the corresponding radiation heat transfer coefficient was $0.39 \text{ W/m}^2\cdot^\circ\text{C}$, which is about 0.45% and 1% compared with the convective heat transfer coefficient for rotating and stationary sphere. And hence, its influence was small and can be neglected in our experiment. On the basis of this assumption, the equation for heat conduction can be defined as:

$$h_c A_s (T_s - T_\infty) = \rho_s V_s C_s \frac{\partial T_s}{\partial t} \quad (2)$$

where h is the heat-transfer coefficient by convection, T_s is the temperature of sphere, T_∞ is the air temperature, t is cooling time, and A_s, V_s, ρ_s , and C_s are the sphere total surface area, volume, density, and specific heat, respectively. The analytical solution of Eq. (2) can be obtained as [17].

$$h_c = \frac{C_p \rho_s r}{3} \left[\ln \frac{(\partial T_s(t)/\partial t)}{(T_s(t) - T_\infty)} \right] \quad (3)$$

This relation means that the heat-transfer coefficient can be obtained by calculating the temperature slope from the cooling curve. Next, we can estimate the average Nusselt number as follows:

$$Nu = \frac{h_c d_s}{k_a} \quad (4)$$

The Bi number is assessed by relation:

$$Bi = \frac{h_c (V_s/A_s)}{k_s} \quad (5)$$

The Reynolds number is obtained by relation.

$$Re = \frac{\rho_a u d_s}{\mu_a} \quad (6)$$

Fourier number

$$Fo = \frac{\alpha t}{R_0^2} \quad (7)$$

Prandtl number

$$Pr = \mu_a \frac{C_p}{\lambda_a} \quad (8)$$

Dimensional rotational speed

$$\Omega = \frac{(r.p.m) \times 2\pi \times R}{60 \times U_\infty} \quad (9)$$

3. Results and discussion

3.1. Validation study with a stationary sphere and composite heat transfer correlation

In order to verify the experimental set-up, the average heat transfer coefficient for steady-state conditions (Nu number) was measured and compared with those obtained from correlations of Romkes et al. [18], and Whitaker [19], as shown in Fig. 3. The experimental data showed that the Nusselt number increases with increasing Reynolds number. From this figure, it can be seen that the measured data are in good agreement with correlations data. In addition, the correlation for Nusselt number of the type $Nu = f(Re, Pr)$ was developed based on the experimental measurements, the resultant correlation is given as follows:

$$Nu = 0.44 Re^{0.59} Pr^{0.33} \quad (11)$$

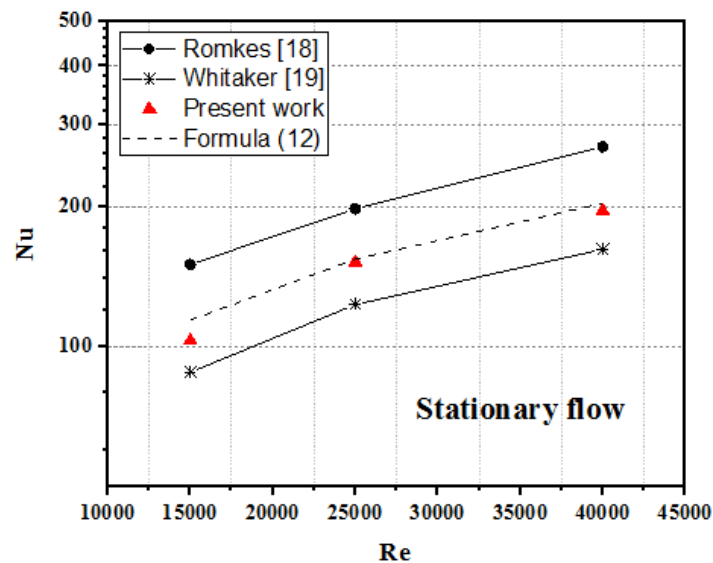


Figure 3. Comparison results of the present work and those obtained from standard model for Nu.

3.2. Heat transfer on a rotating sphere

Experiments were performed to evaluate the influence of the sphere rotation rate on the single-phase heat transfer enhancement using a special-purpose conical diffuser as a passive rotating technique. As we mentioned in the introduction section, the heat-transfer rate of a cooled rotating sphere significantly depends on the rotation rate, surface temperature, and fluid flow rate. We have conducted a number of experiments on sphere cooling under a range of Re number, non-dimensional rotational speed, and surface temperature. During the experiments, air was used as a working fluid. The rotating sphere was balanced dynamically, so the wobbling and vibration effects were reduced to a minimum. The experimental results of surface temperature profile (quench curve) during cooling process vs Fourier number for clockwise rotating heated sphere were shown in Fig. 4. The cooling process was carried out with an initial surface temperature $T_{si} = 300, 200, \text{ and } 100^\circ\text{C}$ and Re number varied from 40000 to 15000. In the case with $\Omega = 0.105\text{--}0.192$, while the surface temperature remains constant (for example $T = 300$), fluid dynamics around sphere increases with rotational speed and diminished the thermal boundary layer, resulting in the increases of the heat transfer rates. Cooling duration from the initial sphere temperature is found to be 260–210s related to rotational speed and Re number. To elucidate the effects of rotational speed on heat transfer enhancement, a comparative study on stationary and rotating spheres was performed. Fig. 5 display the temporal behavior of the surface temperature profile at practically the same conditions for a stationary and rotating sphere. From Fig. 5, it is obvious that the average surface temperature for a rotating sphere with constant Ω starts to quickly decrease until the Fourier number approaches 10 and then changed very slightly in the Fourier number range from 10 to 20. In rotational flow, the influence of rotating speed is shown and it can be noted that the surface temperature reduces as rotational speed increases for constant surface temperature. For constant Fourier number, the surface temperature decreases by about 280% compared with a stationary sphere under the same conditions.

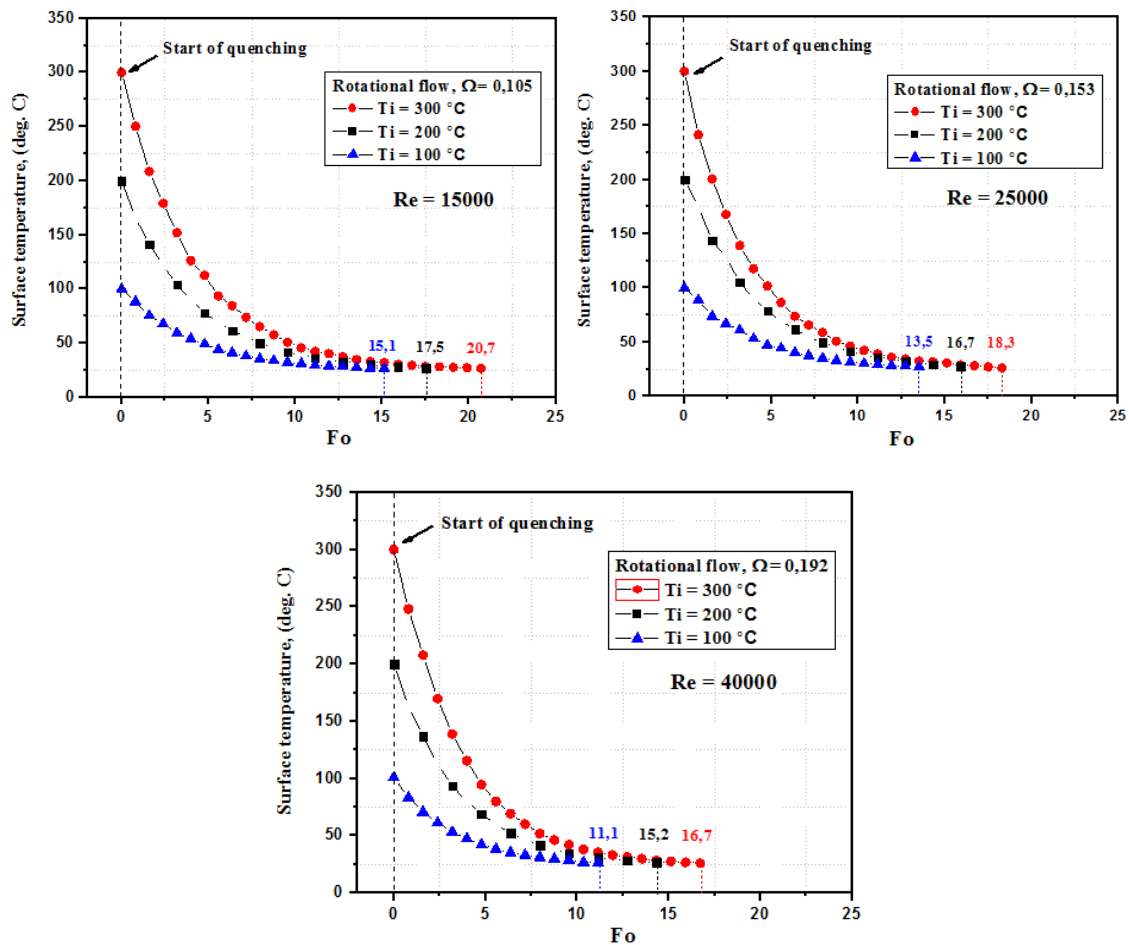


Figure 4. Unsteady temperature profile vs Fourier number for different Re numbers and range of initial temperatures.

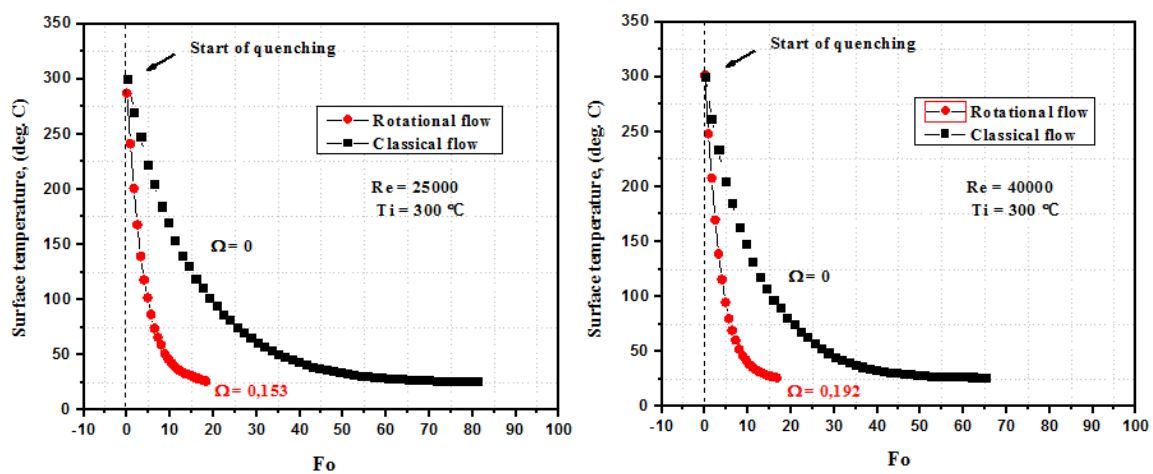


Figure 5. Comparison of the surface temperature profile for a stationary and rotating sphere.

By the direct observations, it was noted that the sphere jet became stronger as Re number increased. At low rotating speeds, the flow pattern becomes distorted and an unsteady turbulent zone was formed in the upper half of the sphere. As the rotational speed increased, a very complex turbulent flow was generated in the wake of a sphere characterized by unsteady vortices. For the stationary sphere, Achenbach [20] discussed in his experimental observation that the vortex loops are formed in the wake of a sphere from the separated shear layer for turbulence regime. As they travel downstream, the loops roll up and then dissipate. During the experiments, we found significant differences between stationary and rotating sphere of heat transfer behavior. The heat transfer behavior in terms of heat flux q and Nusselt number Nu , respectively, expose that q decreases with increase of non-dimensional rotational speed (see Fig. 6), while Nu increases with the increase of non-dimensional rotational speed around 600% as shown in Fig. 7.

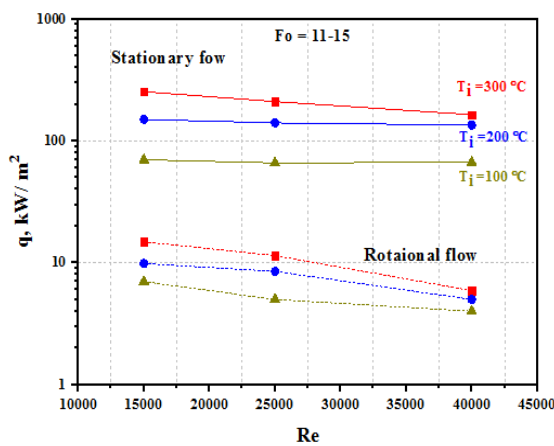


Figure 6. Calculated values of the heat flux density for rotating and stationary spheres at different initial temperatures.

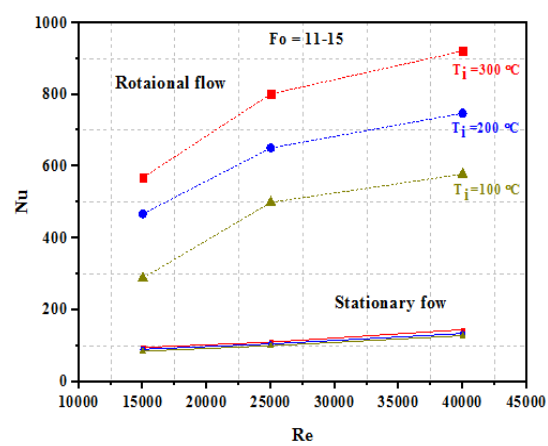


Figure 7. Calculated values of the average Nusselt number for rotating and stationary spheres at different initial temperatures.

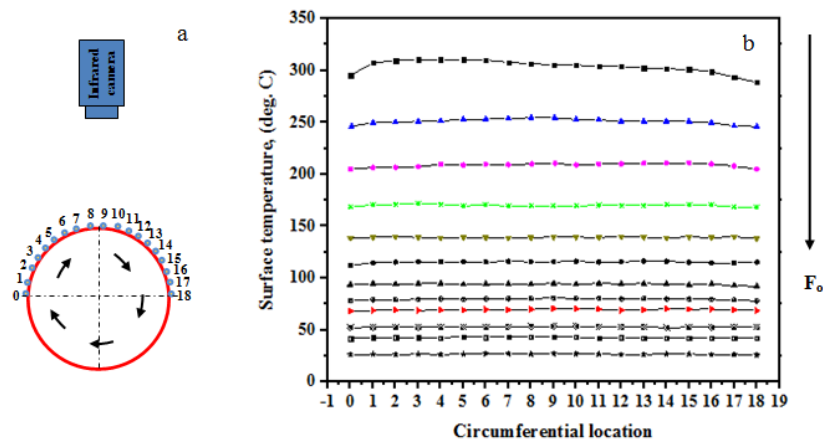


Figure 8. Local point locations at a circumferential location of the rotating sphere (a); surface temperature distribution at different points of the sphere surface (b).

Infrared camera (IR) measurement system was used in this experiment to obtain a local temperature distribution on the sphere surface. This will greatly assist in understanding and confirm the uniform temperature distribution at any point in the sphere surface. After the required surface temperature was achieved, 24 infrared images of the rotating sphere were recorded with a ten-second

interval. For each image, the local surface temperature was averaged circumferentially to obtain the average surface temperature of sphere. Fig. 8 (a) presents 18 local point locations at a circumferential location of the rotating sphere where the temperature is recorded using the infrared (IR) camera. While fig. 8 (b) presents a typical surface temperature distribution at different points of the sphere surface. The initial surface temperature was set at (300 °C), Re number and rotation speed was maintained constant at 40000 and 0.192 respectively. In our experiments, we further examined the longitudinal and transverse temperature distributions along the sphere surface.

Conclusions

An experimental investigation has been performed to elucidate the effects of rotational speed on heat transfer enhancement of the sphere using lumped capacity system as a heat-transfer model. Experiments were carried out with an initial surface temperature $T_{si} = 300, 200, \text{ and } 100 \text{ }^{\circ}\text{C}$, and Re number varied from 40000 to 15000. In case with $\Omega = 0.105\text{--}0.192$, while the surface temperature remains constant (for example $T = 300$), fluid dynamics around sphere increases with rotational speed and diminished the thermal boundary layer, resulting in the increases of the heat transfer rates. In addition, for constant Fourier number, the surface temperature decreases with the increase of non-dimensional rotational speed by about 280%, and Nu increases about 600% compared with a stationary sphere under the same conditions. Using an Infrared camera (IR) measurement system to obtain a local temperature distribution on the sphere surface greatly assist in understanding and confirmed the uniform temperature distribution at any point in the sphere surface.

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